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A study was undertaken to examine stress fracture susceptibility in female US Marine Corps recruits, using anthropometry and bone structural measurements derived from dual energy x-ray absorptiometry (DEXA) scans of the femur and lower leg. A total of 671 recruits received anthropometry and DEXA scans at the onset of training and were followed to ascertain stress fractures. A total of 36 recruits (5.2%) suffered stress fractures; 13 cases were in the foot, 10 each in the pelvic girdle and lower leg, and 9 in the femur. Fracture cases were pooled and compared with non-fracture cases. Results show that BMD, cross-sectional geometry, strength indices, and mean cortical thicknesses of the femur and tibia were significantly lower in cases than in controls, suggesting relatively weaker bone strength of the lower limbs of fracture cases, a result also seen earlier in males. In the male however, small body size predisposed to stress fracture, but in the generally smaller female, body size was unimportant. Moreover male stress fractures were predominantly below the knee (81%), while more than half (53%) of female cases were in the femur or pelvic girdle. When pelvic stress fractures were separately compared to controls, only pelvic and intertrochanteric breadths corrected for body weight, were significantly larger in cases. This suggests that a relatively wide pelvis is a risk factor for pelvic stress fracture and considering the narrow male pelvis may explain why pelvic stress fractures is a female phenomenon.

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Thomas Bell 10-20-97

PI - Signature Date

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INTRODUCTION

Stress fractures cause significant morbidity during recruit training, particularly for elite programs requiring intense physical conditioning such as the US Marine Corps[1-3]. Estimates of the incidence of stress fractures among female military trainees range from as high as 34% to as low as 1.1%[4-7]. Data from Marine Corps Parris Island[8] indicate that women suffer lower extremity stress fractures at a rate of 3.8% a rate comparable to that of males. More recent data from an associated study indicates that the stress fracture rate in the current female cohort is about 5%[1]. The primary fracture site is in the metatarsals, although pelvic and femoral stress fractures constituted more than half of the total (ibid.).

The impact of stress fractures on training and on operational readiness is significant. While stress fracture is not the most prevalent injury among recruit populations, the cost of each occurrence is high. Recent data on male recruits at MCRD San Diego show that with an incidence rate of 3.7%, lower extremity stress fractures cause a loss in training time of 35-69 days and costs on the order of $4 million annually for that site alone[2]. Although the numbers of female recruits is smaller, the number of costly above-the-knee fractures in females is far greater.

Stress fractures, which predominantly occur in the lower extremity and pelvic girdle, are believed to result from structural failure in the bone caused by repetitive weight bearing loads. Weight bearing under training regimens subjects bones of the lower limbs to repetitive axial compression, torsion and bending stresses[9]. Within a bone subject to a given load, stress magnitudes are determined by bone structural geometry, while the bone's ability to resist these stresses is defined by bone material properties. [10]. Since bone material properties are much less variable than structural geometry, it is likely that most of the individual differences in bone strength can be explained by geometry[11]. Moreover there is evidence that bone material properties may not vary significantly with age as was previously believed[12]. For a given long bone, the most important geometric properties are the cross-sectional area (CSA) and for bending in a plane, the cross-sectional moment of inertia (CSMI). These structural properties in the long bones of the lower extremity are known to vary with age and sex in the human and may relate to the ability of aging bone to alter the CSMI to compensate for increased mechanical stresses due to bone loss in osteoporosis[13]. There is also evidence that bone is structurally remodeled to minimize stresses in limbs subjected to increased loads over shorter time scales; moreover these changes are evident in the cross-sectional properties[14]. The implication for younger populations is that bone can be strengthened by rigorous training. Unfortunately, information regarding the rates and magnitudes of such change and in the factors influencing such change in the human are scanty. The current project includes an assessment of geometric changes in the lower limbs of female Marine Corps recruits. Such data should have significant implications in the design of future recruit training programs as well as in the design of remediation regimens for those with structurally weak bones.

This project involves the acquisition of data to support two separate hypotheses. The first is that those structural geometry properties measured in the lower limb that were found to be associated with lower limb stress fractures in male Marine Corps recruits [15], will exhibit a similar association in female recruits. The second hypothesis is that the intense training regimen in female Marine Corps recruits will produce changes in the structural geometry of the lower limb bones that are indicative of improved bone strength.

BODY

Materials and Methods

A cohort of female recruit volunteers were given a consent form during the first week of recruit training and then administered a questionnaire soliciting general background information issues (diet, exercise, menstrual, smoking, skeletal injury, history etc.) administered for our colleagues at the Naval Health Research Center in San Diego. A subset of these recruits were administered a second informed consent to participate in the current study which included DEXA scans and anthropometric measurements. A randomly selected sample of these volunteers was selected for further measurements. Measurements included height, weight, neck waist and hip girths, thigh and calf girths as well as the lengths of the upper and lower right leg, the girths of the pelvis between the iliac crests, the hips between the greater trochanters, and the knee at the level of the femoral condyles. Subjects were then scanned with a conventional dual energy x-ray absorptiometry (DEXA) scanner at both the mid shaft of the right femur and at the distal third of the lower right leg. The entire cohort was followed to ascertain the incidence of stress fractures and other musculoskeletal injuries. To address the second hypothesis, a subset of recruits receiving measurements at the beginning of training, were re-scanned during the last week of training, and those anthropometric measurements (weight and girths) likely to change were also repeated. In this part of the study the effect of the standard training regimen on the normal skeleton is being evaluated hence all recruits with sufficient injury to cause interruption of training, or any recruits undergoing more than 12 weeks of training were excluded.

A third part of the study involves the use of relative lean muscle mass measurements provided by the DEXA scanner from the measurement at the mid thigh. One of the functions of muscle is to resist the bending stresses on the bones due to physical activity. Conceptually, women with lower relative muscle mass may be deficient in this respect, and thus more susceptible to stress fracture. We are also exploring the use of these measurements as indices of fitness by comparing them with the initial strength test scores recorded for recruits during the initial evaluation of recruits.

To derive the structural geometry from the DEXA scan data, scan files were transferred to our laboratory for analysis, using programs described previously(15). In addition to the conventional cross-sectional properties computed for the bones of the femur and lower leg, we have also calculated the "whole bone strength index" after Selker and Carter (16), as the ratio of section modulus (Z) to bone length. This index based on the observation that strength of a bone under bending or torsion (the conditions of military training) the strength is inversely dependent on the bone length and directly related to the section modulus. Also since critical failure may be related to cortical thickness, a measure of cortical thickness may be desirable. Because a direct measure cannot be derived from the DEXA data, a mean cortical thickness(t_b) for an equivalent circular annulus was computed as:

$$t_c = \frac{w}{2} - \sqrt{\left(\frac{w}{2}\right)^2 - \frac{CSA}{\pi}} \qquad [1]$$

where w is the measured bone width. This parameter was computed for all three bones, although the assumption of a circular annulus is reasonable for the femur and fibula, it is less appropriate for the tibia.

A significant problem in the male stress fracture study, was under-reporting (15), due to the failure of injured recruits to go to sick call. As in that study, a follow-up procedure conducted

at the end of training was initiated to ascertain whether the actual stress fracture rate was greater than that reported by self-referral to sick-call.

Statistical analysis of results was done with StatView for the Macintosh (Abacus Concepts Inc., Berkely CA).

Results

At the end of data accrual in September 1996 a total of 693 recruits were enrolled and anthropometric measurements were obtained. Of these recruits 671 received DEXA scans. (Technical problems with the scanner or logistical problems prevented scanning in 22 recruits). For the second part of the study, a total of 175 enrolled recruits were re-scanned at the end of training although 203 recruits received pre and post training anthropometric measurements.

A total of 36 recruits suffered stress fractures during the follow-up period, corresponding to a fracture rate of 5.2%. Details of the ascertainment of underreporting will be forthcoming, but suffice it to say that no significant under-reporting of stress fractures was evident in this data set unlike the experience in males[15]. Of the 36 recruits with fractures 11 had fractures at two locations, and one recruit suffered four stress fractures. For classification purposes, fractures were categorized as 1) pelvic girdle (includes sacrum), 2) femora, 3) lower leg (tibia or fibula), or foot (tarsals, or metatarsals). A total 13 recruits had stress fractures of the foot, 10 each had pelvic girdle and lower leg fractures, and nine fractures were in the femora. Because fracture incidence was small, cases were pooled and measured characteristics were compared with non fracture cases.

Anthropometric variables:

Comparison of mean values by t test indicate that no anthropometric variable was independently different between groups at the $p < .05$ level of significance. This included, height, weight, body mass index, lengths of the thigh and tibia, and girths of the neck, waist, hip, and thigh as well as breadths of the pelvis, hips and bicondylar dimensions at the knee. Calf circumference was marginally smaller in fracture cases ($p = .103$).

Bone Geometry And Mass Variables

Conventional bone mass as well as derived cross-sectional geometry variables measured at the mid-shaft of the femur and distal third of the tibia, were except for tibial width, significantly smaller in cases than controls. The average values of cases and controls, in bone mass, cross-sectional properties and widths are listed individually for the femur, tibia and fibula in Table 1. Also shown are the differences between the two groups and the significance (unpaired two tailed t-test), of the differences. Also shown are strength indices computed as the ratio of section modulus to bone length, based on the observation that strength of a bone in bending or torsion, is inversely related to the length of the bone and directly proportional to its section modulus. Also note that the average cortical thickness is significantly smaller in cases than in controls, for all three bones. The magnitudes of these differences between cases and controls can be seen graphically in Figure 1. The DEXA measured relative muscle mass a the thigh also was significantly smaller in fracture cases, indicating that subjects with fractures had less muscular thighs, while their thigh girths were not significantly smaller.

Table 1: Average values of bone mass and geometric variables measured in the femur, tibia and fibula, for stress fracture cases and controls. (All measurements are expressed in powers of cm, rather than mm).

Parameter	Fracture Cases (pooled)	Controls	Percent difference	Significance
Femur BMD (g/cm^2)	1.296	1.371	-5.5%	0.0002
CSA (cm^2)	2.630	2.860	-8.0%	0.0001
CSMI (cm^4)	0.994	1.138	-12.7%	0.0025
Width (cm)	2.140	2.200	-2.7%	0.0238
Section Modulus (Z) (cm^3)	0.921	1.023	-10.0%	0.0010
Strength Index (Z/femur length)	1.829	2.012	-9.1%	0.0013
Average cortical thickness (cm)	0.518	0.559	-7.3%	0.0016
Tibia BMD (g/cm^2)	0.952	1.020	-6.7%	0.0004
CSA (cm^2)	1.669	1.822	-8.4%	0.0005
CSMI (cm^4)	0.472	0.532	-11.3%	0.0271
Width (cm)	0.185	0.189	-2.1%	ns
Section Modulus (Z) (cm^3)	0.502	0.556	-9.7%	0.0088
Strength Index (Z/femur length)	1.384	1.493	-7.3%	0.0276
Average cortical thickness (cm)	0.359	0.392	-8.4%	0.0018
Fibula BMD (g/cm^2)	0.533	0.559	-4.7%	0.0321
CSA (cm^2)	0.541	0.570	5.1%	ns
CSMI (cm^4)	0.046	0.050	-8.0%	ns
Width (cm)	0.107	0.108	-0.9%	ns
Section Modulus (Z) (cm^3)	0.084	0.091	-7.6%	ns
Strength Index (Z/femur length)	0.233	0.245	-4.9%	ns
Average cortical thickness (cm)	0.199	0.213	-6.6%	0.0315
Relative Thigh Lean Mass	0.736	0.764	-3.7%	0.0088

[redacted]

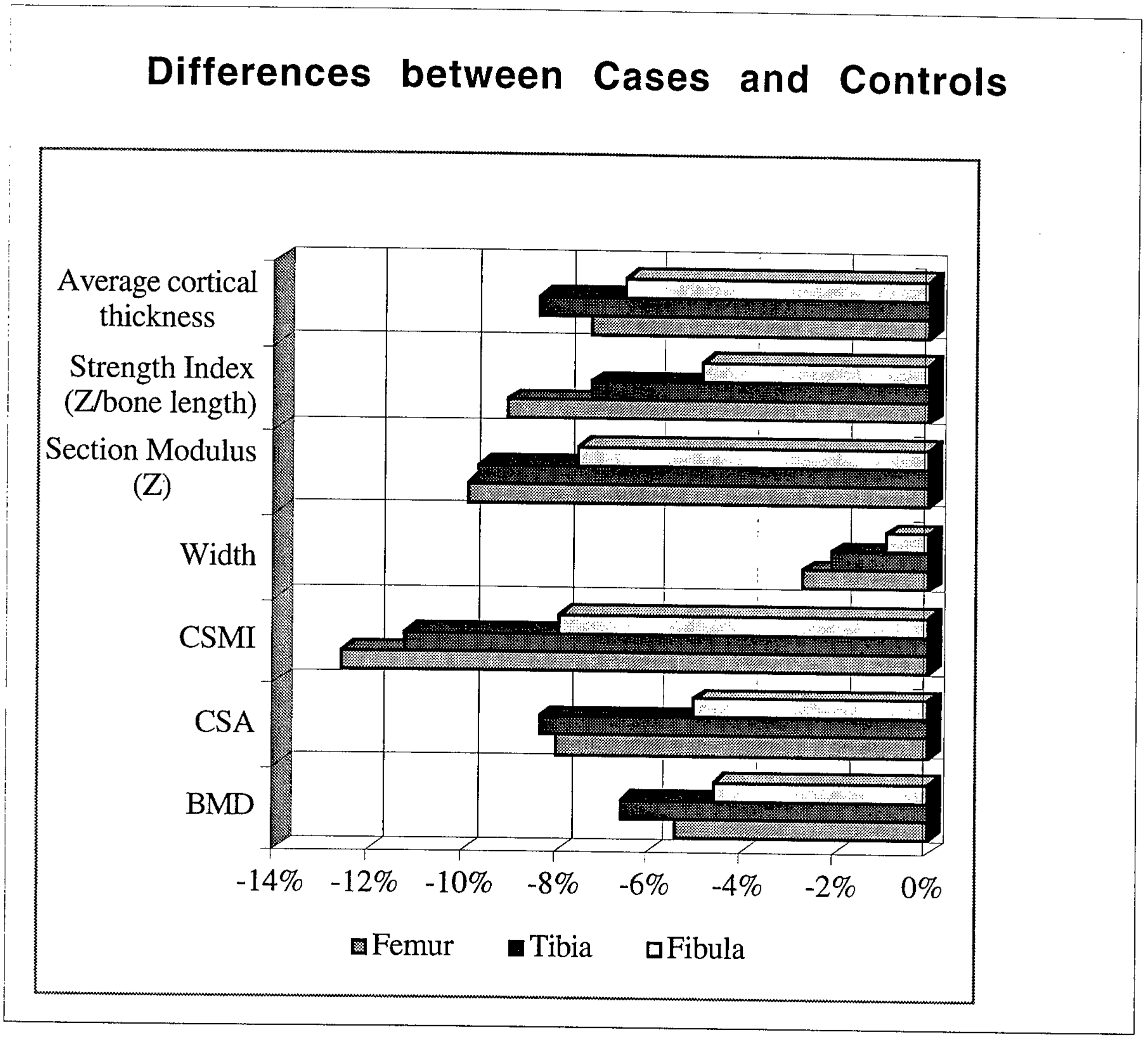

Figure 1: Percent differences between stress fracture cases and controls for bone mineral density and for structural geometry variables (not all differences were statistically significant, see Table 1 for significance).

Discussion

Analysis of the results of the study are not yet complete, some follow-up data is incomplete and due to technical problems some scan data will have to be re-analyzed in the final year of the study. One manuscript is in preparation comparing results to those observed in the study of male Marine Corps recruits(15). A second manuscript is planned for the longitudinal changes in bone due to training. There are nonetheless, significant differences between the male and female results. First, stress fractures above the knee are relatively infrequent in males (19% of cases) but constituted 53% of cases in the female. Fractures of the pelvic girdle did not occur in our series on the male, while these fractures constituted 28% of cases in the female. It is also worth noting that in males, most fracture cases were smaller in height, weight, BMI, and girths at all locations, although indices of skeletal size (pelvic width) and joint size (bicondylar breadth) were not. In contrast, none of these parameters were significantly different in the female, indicating that female fracture cases were not generally smaller in body size than controls.

The general results indicate that like in the male, fracture cases tended to have relatively narrow bones, moreover the mean cortical thickness was also smaller at all locations (not yet done in the males). Differences between cases and controls are generally greater in the weight bearing femur and tibia and smaller and generally not significant in the non-weight bearing fibula. A composite measurement which take into account bone size as well as stiffness, the strength index, was significantly smaller in fracture cases for the femur and tibia. This result corrects the section modulus for bone length (not significantly different in the female) indicates that bones of cases tend to be less stiff although not different in length. We found that the strength index was also smaller in male stress fracture cases (unpublished data), which also had shorter bones.

Regarding these differences between cases and controls, one question that comes to mind is that to what extent are they genetic, and to what extent are they environmental, (i.e., exercise)? Animal and human data[9, 17-19] suggests that hypertrophy from exercise can increase the bone section modulus, thus improving the resistance to bending stress. This measurement taken with the lower relatively lean mass in the female fracture cases suggest a lower level of fitness. Comparison of strength test scores is under way but incomplete due to some missing and questionable values. Some preliminary differences are shown in Table 2.

Table 2: Comparison of strength test data between cases and controls. IST refers to initial strength test done prior to initiation of training, while PFT is the performance fitness test, which are done at intervals through the 12 week training period. The last entry is the difference between the run scores (times in seconds to run a 1.5 mile course).

Parameter	Fracture Cases (pooled)	Controls	Percent difference	Significance
IST sit-ups	32.47	34.841	-6.8%	(0.0515)
IST run score (time in s)	636.7	624.1	2.0%	ns
Initial PFT sit-ups	40.75	42.8	-4.8%	(0.079)
Initial PFT run score (time in s)	1267	1219	3.9%	0.0156
Change in run scores PFT 1- PFT2	0.031	0.06	-48.3%	0.0180

Table 2 shows significant differences in performance of the 1.5 mile run between cases and controls, moreover the improvement in run scores was significantly higher in controls compared to fracture cases. The numbers of sit-ups on the initial strength test and on the first performance test were smaller in cases than controls but differences are not quite significant. These data suggest that cases are less physically prepared for the rigors of recruit training.

We had hoped that DEXA scan data from recruits taken before and after training would support the hypothesis that the strength properties are malleable by training. However, results are unclear and analysis is not yet complete (a minor error in the analysis program may require repeating of the computer analysis). It is also likely that the 11-12 week time scale between scans is inadequate to show appreciable training effects, given the quality of the scan data and the longer time scales (months to years) required to show significant remodeling[20].

There may remain a component of genetic susceptibility to stress fracture independent of training effects. One observation from the current study is that the pelvic stress fractures appear to be a different group from the lower extremity fracture cases. In fact, while the structural properties in the femur and lower leg were smaller in pelvic girdle fracture cases than controls, the differences were not significant, unlike the result with the pooled case comparison. The only things that appeared to be different in pelvic girdle fracture cases were that after correcting for body weight, the intertrochanteric and pelvic breadths were <u>larger</u> in fracture cases than in controls. This makes some sense since a relatively wider pelvis should flex and twist more under intense physical activity compared to a narrower pelvis, assuming constant geometry of

the pelvic struts (pubic and ischial rami). In order to pursue this hypothesis it would be necessary to make direct measurements of pelvic bone geometry, which is apparently not well characterized by remote DEXA measurements in the femur and lower leg.

CONCLUSIONS

Analysis of the results of this study on DEXA derived structural indices of stress fracture incidence in female Marine Corps Recruits is not yet complete. Nevertheless the structural geometry parameters measured in the femur and lower leg were significantly lower in pooled cases of stress fracture compared to controls. This result, clearly indicating lower biomechanical strength in the bones of the lower limbs of stress fracture cases, was also seen in male stress fracture cases in an earlier study. There were however important differences between the male and female results. In the male, small body size, generally predisposed to stress fracture, whereas in the female, with generally smaller body sizes overall, body size was not an important predictor of stress fracture. Moreover the distribution of stress fractures in males is predominantly below the knee (81%), while more than half (53%) of stress fractures in the female, occurred in the femur or pelvic girdle. Interestingly, when fractures of the pelvic girdle were separately compared to normal controls, only pelvic and intertrochanteric breadths corrected for body weight, were significantly different in fracture cases. These latter values, larger in cases, suggest that a relatively wide pelvis is a risk factor for stress fractures of the pelvic girdle. This observation together with the naturally narrower pelves in the male may explain the lack of pelvic girdle stress fractures in the male.

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